Ratio measurement techniques

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RATIO-MEASUREMENT TECHNIQUES

INTRODUCTION

A great many voltage measurements have, as their basic objective, the comparison or ratio of two voltages. This is true, particularly, in the testing of devices such as amplifiers and transformers, which generate a transfer function. The absolute values of the input and output voltages are not as important as the ratio between the two. Similarly, when devices such as vibration transducers are tested against a standard transducer, the objective is to develop a calibration factor or ratio between the two outputs.

The measurement of the ratio as a calculated value derived from two absolute voltage measurements is time consuming, subject to operator error, and most important, is limited in accuracy by the stability of the energy source. All of these objections are eliminated by the use of a ratiometer which detects both voltages simultaneously and produces a ratio value in real time.

Such an instrument makes it possible to measure ratios rapidly and under dynamic conditions. The transfer function of a device may be examined as a function of input voltage, frequency, and time, in a single series of measurements, by varying the amplitude and signal frequencies across the desired ranges and recording the data at precise intervals to detect any time drift due to such factors as self heating. Time intervals between absolute measurements would tend to mask such drift characteristics.

Ratiometers to perform measurements like these should ideally have the following characteristics:

1. A real-time ratio-taking capability.
2. The ability to measure ac/ac, ac/dc, and dc/ac ratios, as well as the more usual dc/dc ratios.
3. Phase independence in the case of ac/ac measurements.

4. High input impedances for both the signal (numerator) and reference (denominator).
5. Fast digitizing time.
6. High accuracy, ideally higher than that obtained in taking absolute measurements against an internal reference.

Instruments of this type are relatively new. The purpose of this paper is to examine their use and to summarize the instrumentation techniques that may be employed to enhance their performance.

RATIOMETER DESIGN

Figure 1 presents a simplified block diagram of a general-purpose ratiometer of the null-balance type.

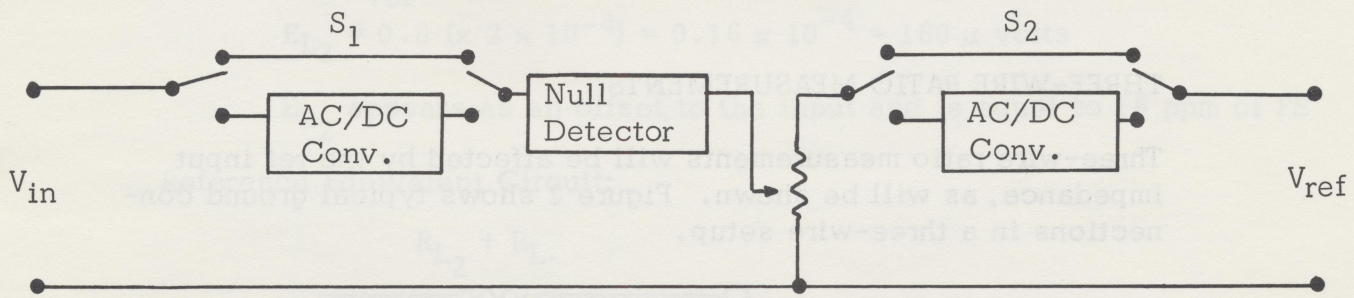


FIGURE 1.

By appropriate operation of switches S_1 and S_2, ratio combinations such as ac/ac, ac/dc, dc/ac, and dc/dc may be performed. To make ac/ac measurements, two ac converters are required. The desired characteristics of the ac converters is that their frequency response and settling time be similar for those conditions where f_{in} equals f_{ref} and that their frequency response be flat for the cases when the two frequencies are not equal.

AC converters for ratiometer use are designed to have fast and similar settling times in order to reject to a high degree oscillator amplitude modulation and converter ripple. Stable, uniform converters with high ac resolution make it possible to take ac/ac ratio measurements to

an accuracy of 0.03% even when the individual converter has an accuracy specification of only 0.1%

The null detector in Figure 1 must have high sensitivity and low noise, if it is to operate over a wide range of reference voltages. If we assume a 5 decade instrument with a nominal 10 volt reference, one digit represents 100 μ volts. If the reference voltage is decreased to 1 v, one digit represents a 10 μ volt change in the input signal.

To operate over a wide range of reference voltages, then the null detector must have a gain control in order to achieve stability if the logic is of a tracking type or the gain will be low and errors will occur for low reference voltages. However, if the logic is of the successive approximation type, that is, each reading is a separate and complete reading and does not rely on an absolute null to be stable, the gain can, in theory, be made infinitely large. The limiting factor now is noise.

THREE-WIRE RATIO MEASUREMENTS

Three-wire ratio measurements will be affected by the ref input impedance, as will be shown. Figure 2 shows typical ground connections in a three-wire setup.

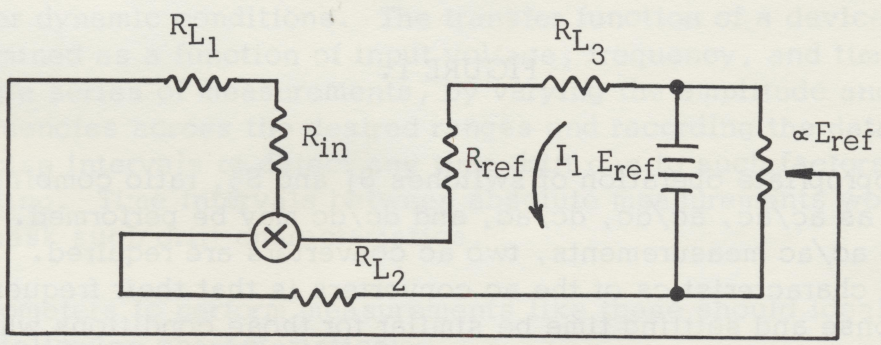


FIGURE 2.

R_{in} is the input resistance of the ratiometer
R_{ref} is the reference input resistance of the ratiometer
R_{L_1}, R_{L_2}, R_{L_3}, are lead resistances

Ⓧ = DVM common

The true reference voltage as seen by the ratiometer appears across R_{ref}. Voltage drop in R_{L_2} and R_{L_3} is subtracted from E_{ref} causing an error in the reference voltage seen by R_{ref}. The drop across R_{L_2} also appears as an input signal and is constant for a given reference and input leads.

To examine the magnitude of the errors possible, assume RG-174 cable, a 10 volt reference, and 50,000 ohms for R_{ref}. Assume an 8-foot input cable.

RG-174 cable is approximately 100 milliohms/foot.

Let

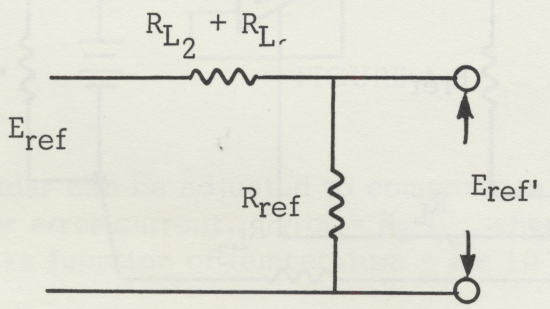
$$R_{L_1} = R_{L_2} = R_{L_3} = 800 \text{ milliohms}$$

$$I_1 = \frac{E_{ref}}{R_{ref}} = \frac{10}{50} \times 10^{-3} = \underline{\underline{0.2 \text{ ma}}}$$

$$E_{L_2} = 0.8 \ (\times 2 \times 10^{-4}) = 0.16 \times 10^{-4} = 160 \ \mu \text{ volts}$$

E_{L_2} appears as an offset to the input and is equal to 16 ppm of FS

Reference Equivalent Circuit:



$$E_{ref'} = E_{ref} \left(\frac{R_{ref}}{R_{ref} + R_{L_2} + R_{L_3}} \right)$$

$$\text{error in } E_{ref} = E_{ref} - E_{ref'} = \left(1 - \frac{R_{ref}}{R_{ref} + R_{L_2} + R_{L_3}} \right)$$

$$\text{for above case, \% error} = \frac{160}{5 \times 10^4} = 0.0032\%$$

Therefore, 8 feet of RG-174 input cable and a reference input resistance of 50,000 ohms will cause a 0.0032% of reading error and 0.0016% of FS error.

At full scale, these effects are subtractive, since the reference voltage is 0.0032% low, causing the reading to be 0.0032% high, and the 0.0016% of FS appears as an offset in the negative direction for a positive reference. The total error at full scale is 0.0016%.

However, at 10% of full scale, the percent of reading error becomes insignificant and the percent of full scale dominates. The percent of reading error is now 0.016%.

The offset voltage due to lead resistance in R_{L_2} is the more serious error offender. It is, therefore, desirable to keep current I_1 to a minimum value by maintaining a large value of R_{ref}.

Figure 3 shows a setup to accomplish this <u>within</u> the ratiometer by the addition of a buffer amplifier, A.

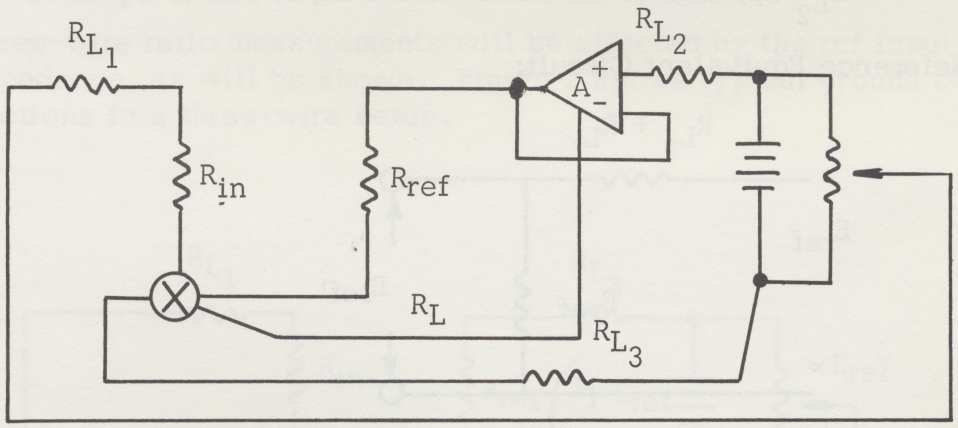


FIGURE 3.

Amplifier A presents a high resistance to the reference, thereby minimizing current flow in the reference return line R_L. Amplifier A can be designed with gain accuracies and linearity in the order of parts per million and a very high input resistance. The greatest error appears

as an offset current or current error. For a well-designed solid-state amplifier, this value can be kept to less than 100 nanoamps absolute and less than 1 nanoamp/°C. $E_{R_L} = 0.8\ (0.2) \times 10^{-6} = 0.16\ \mu$ volts.

With a buffer amplifier of this type, 100 volt reference voltages can be handled by placing a divider at the reference source scaling the reference to 10 volts(10:1 divider). However, if the divider is part of the ratiometer, the problems of low reference resistance as outlined before are present. Therefore, the preferable hookup is that shown in Figure 4, with a suitable divider consisting of $R_1 = 90$ k and $R_2 = 10$ k.

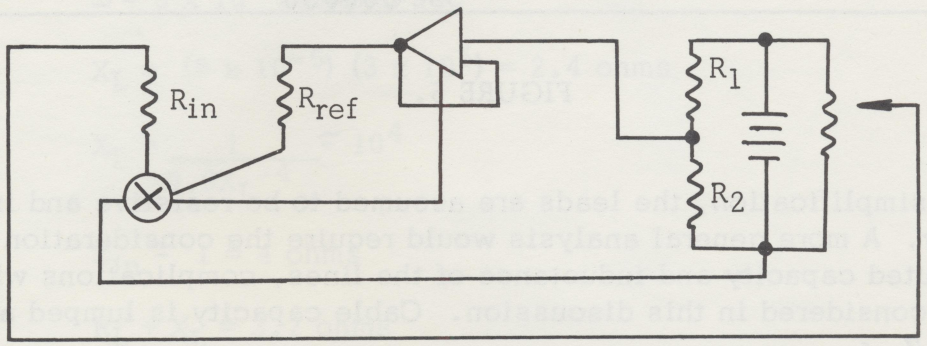


FIGURE 4.

The divider can be adjusted to compensate for the error due to the amplifier error current. Error = $R_2\ I_A$, where I_A = amplifier error current as function of temperature = 1×10^{-9}/°C.

Error = $1 \times 10^{-9}\ (10^{+4}) = 1 \times 10^{-5} = 10\ \mu$ volts/°C = 1 ppm/°C

Therefore, by providing a high input resistance and with the proper placement of dividers for high voltage operation, three-wire ratio operation is possible, even where lead lengths may be of considerable length.

An additional benefit of using a divider for the 100 volt reference is that an additional reference range is gained. With a 100 volt reference and 10 volt FS input, the full scale ratio range is 0.1. Ratios can be read to 1 ppm resolution with a five decade instrument.

AC MEASUREMENTS

Lead resistance problems become more severe when considering ac signal fources. Consider the circuit shown in Figure 5.

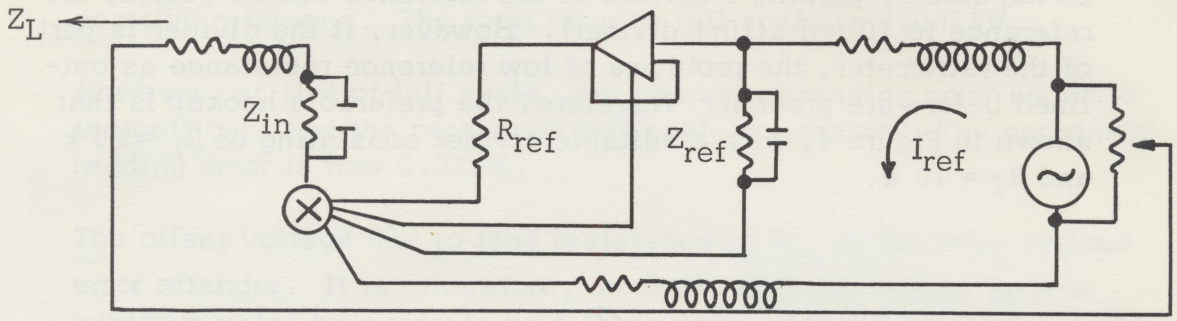


FIGURE 5.

For simplification, the leads are assumed to be resistive and inductive only. A more general analysis would require the consideration of distributed capacity and inductance of the lines, complications which are not considered in this discussion. Cable capacity is lumped at Z_{in} and Z_{ref}.

$L = 1\ \mu h/foot$

$R_L = 0.1$ ohm/foot

$R_{in} = R_{ref} = 10^6$ ohms

$C_{in} = C_{ref} = 47$ pf + 30 pf/foot

For an 8-foot cable:

$R_L = 800$ milliohms

$C_{in} - 300$ pf

$L = 8\ \mu h$

$$Z_{in} = Z_{ref} = \frac{R_{in}\frac{1}{f\omega L_{in}}}{R_{in} + \frac{1}{f\omega L_{in}}}$$

The two effects to be examined are the error in the reference voltage and offset voltages due to I_R.

At low frequencies, the analysis is similar to the dc case. $E_{ref} = 10$ volts.

$$I_{ref} = \frac{10 \text{ volts}}{10^{+6}} = 10^{-5} \text{ amps}$$

$$E_{offset} = 0.8 \text{ ppm of FS}$$

$$E_{ref\ error} = 16 \text{ ppm of reading}$$

As frequencies increase, the error is magnified. For example:

$$\omega = 3 \times 10^5 \text{ radians/sec}$$

$$X_L = (8 \times 10^{-6})\ (3 \times 10^5) = 2.4 \text{ ohms}$$

$$X_L = \frac{1}{0.9X_L{}^{-4}} \simeq 10^4$$

$$Z_{in} \simeq 1 = 4 \text{ ohms}$$

$$R_L + X_L = 3.2 \text{ ohms}$$

$$\% \text{ of FS error} = \frac{320}{10^4} = 0.03\% \text{ of full scale}$$

$$\% \text{ of reading} - 640 \times 10^{-4} = 0.064\% \text{ of reading.}$$

At full scale, the error is equal to 0.09%, since the effect is now additive. At 10% of FS, the percent of reading error is 0.6%.

For a given set of input cables, the percent of reading error can be compensated for by calibration of the reference ac converter. However, the percent of FS error cannot be compensated readily. Short leads are desirable where high frequency measurements are required.

FOUR-WIRE RATIOMETER

Consider the circuit shown in Figure 6. By the addition of an external differential amplifier, A_2, four-wire ratio measurements are possible. The system accuracy is dependent on the properties of A_2. Gain inaccuracies, linearity, common mode rejection and drift of A_2 will limit the ultimate accuracy. Amplifiers are available with gain and linearity accuracies of 0.01%, with less than 1 microvolt/°C drift and 120 db common mode rejection.

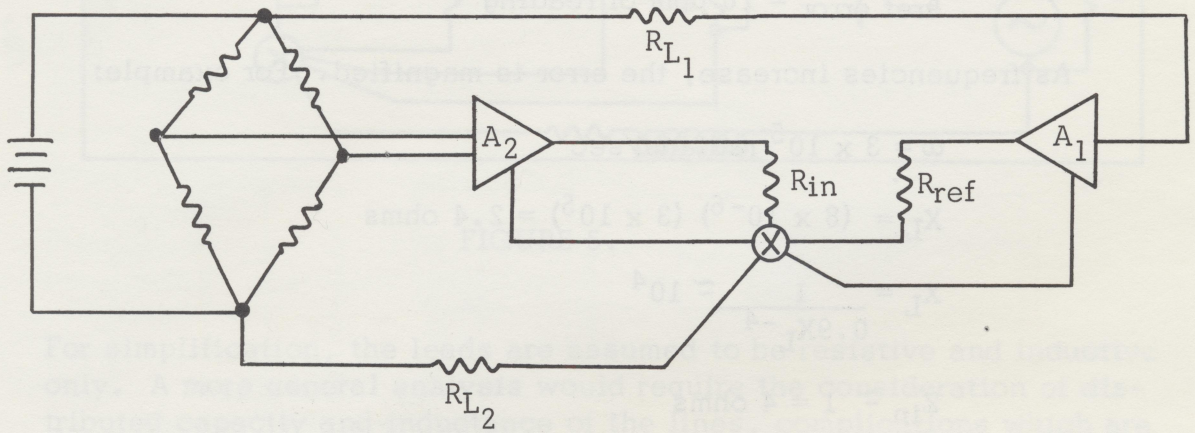


FIGURE 6.

Reference return current is less critical in this application, since drops in R_{L_2} appear only as common mode voltage to amplifier A_2. Drops in R_{L_1} and R_L which would affect the true reference voltage could be trimmed out by adjusting the gain of A_2.

By inserting an ac converter after A_2 and A_1 and substituting an ac generator for the battery shown, the bridge characteristics can be examined over a range of frequencies.

The ac excitation method has the further advantage that by using a low frequency where the reactance of the bridge is negligible, drift or thermal voltages in the test setup can be eliminated. For production testing where bridge characteristics only are desired, this can mean a saving time and better accuracy by eliminating the need for checking and setting zero.

LOW LEVEL RATIO MEASUREMENTS

In dc applications where the excitation voltage to the device becomes very small, the greatest source of error is zero drift. For example, consider Figure 7. The measurement is to determine the gain, A, of the amplifier. If the measurement is made at dc, assume the following parameters:

Ref = ±10 volts
Amplifier output maximum = ±10 volts
Amplifier gain = 1000
Divider is a 6-dial Kelvin Varley with 100 m linearity
Divider input resistance = 10,000 ohms

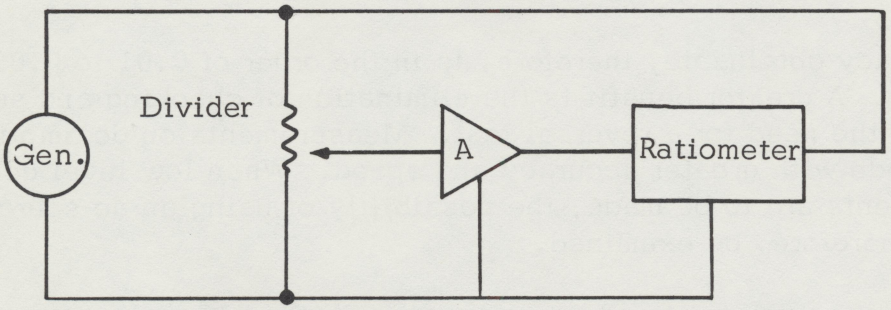


FIGURE 7.

The divider is set to $\frac{1}{A}$, when A is the nominal amplifier gain. Deviation can be read directly on the ratiometer. For example, if the gain is exactly 1000, the divider setting is 0.001, and the ratiometer reading is 1.0000. If the gain is in error by -0.05%, the reading is 0.9995. However, for a gain of 1000, the equivalent input voltage is 10/1000 = FS. To achieve a 0.01% measurement, the error input voltage must be less than $\frac{10 \times 10^{-3}}{10^{+4}} = 1$ μ volt

To maintain a less than 1 μ volt dc error requires careful selection of the test setup, leads and zero adjustment. If the zero should shift during the measurement, an apparent error in gain will be observed. With care, 2-3 μ volts might be obtainable in a production test, which would give a 0.02-0.03% of FS error. The divider accuracy was given as 1 ppm, or at a setting of 0.001 is equal to 0.1%.

The best obtainable accuracy of the dc system is 0.1% of reading +0.03% of FS.

Also, a two-step test should be performed with plus and minus signals to test the amplifier output for both polarities.

For a good wideband dc amplifier, the gain accuracy should be flat to 100 cycles or more. If the dc excitation is replaced with an ac source and the dc divider is replaced with a good ratio-transformer, the following advantages are gained:

The zero-drift term is eliminated. The amplifier output is tested in both polarities simultaneously, and the accuracy of the ratio-transformer is greater than that obtainable with a dc divider. A seven-dial ratio transformer is capable of accuracies of 0.1 to 0.5 ppm. The ratio-transformer also presents a lower and more constant output impedance than is possible with the resistive divider.

The accuracy obtainable, therefore, is in the order of 0.01 to 0.05% of reading. A greater benefit is the elimination of checking and setting zero, and the need for a reversal test. Measurements on dc amplifiers can be made with greater accuracy and speed. When low level dc measurements are to be made, the possibility of using an ac source should, therefore, be examined.

When the measurement involves ratios greater than 10 or less than 0.1, the use of external dividers can enhance the performance.

The principles involved in the example can be extended to many measurement problems, involving transducers, as well as amplifiers, networks, and components.

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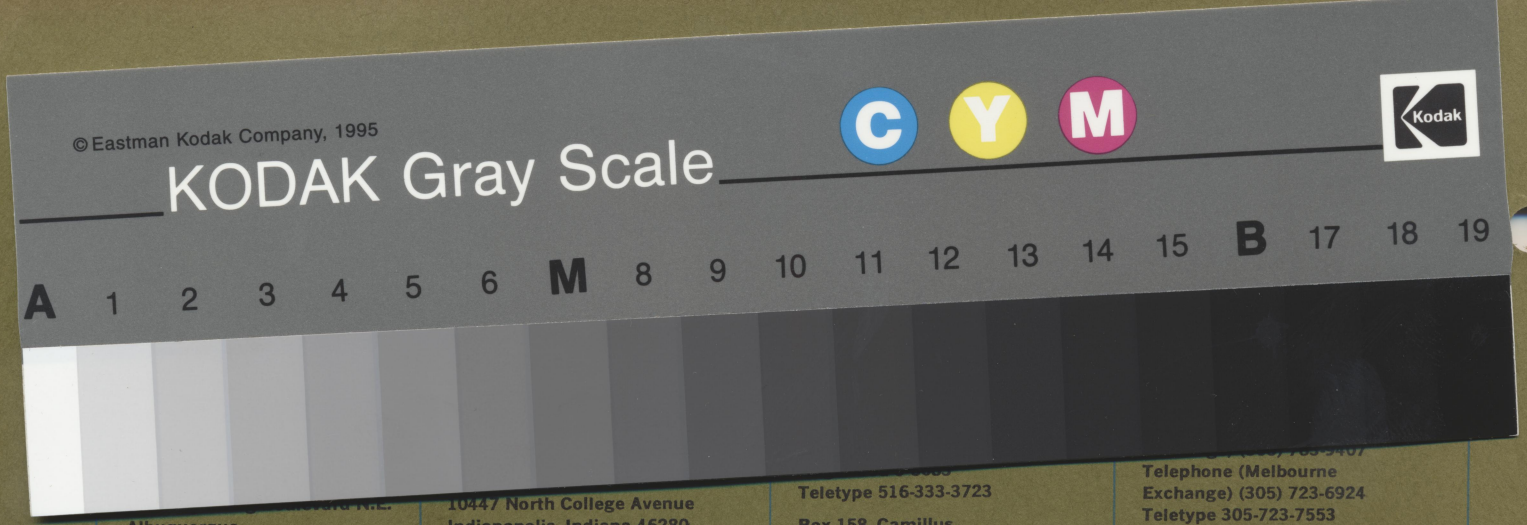

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